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INVESTIGATION OF THE DYNAMIC STABILITY AND CONTROLLABILITY OF A TOWED MODEL OF A MODIFIED HALF-CONE REENTRY VEHICLE

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Technical Film Supplement L-841 available on request.

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SUMMARY

An investigation of the low-speed dynamic stability and controllability of a 1/3-scale model of a modified half-cone reentry vehicle in towed flight has been made in the Langley full-scale tunnel by means of flying-model tests. The model was tested with and without artificial damping in roll and in yaw. Tests were made through a towline-angle range from -5° (high tow) to 6° (low tow).

The investigation showed that, in general, the model had satisfactory longitudinal stability and control characteristics but unsatisfactory lateral stability characteristics due to a combination of a lightly damped Dutch roll oscillation and an unstable long-period oscillation in which roll and sidewise motions were large in comparison with yaw displacements. The adverse motions could be controlled fairly easily with either coordinated aileron and rudder control or rudder-alone control but not with aileron-alone control. This combination of stability and controllability was considered unsatisfactory for general operation but acceptable for relatively short periods of operation under visual conditions. The addition of artificial damping in roll made the flights smoother and the control easier, but the model was still unstable; the addition of artificial damping in yaw made the model stable, but the rolling motions were damped only moderately well; and the addition of both damping in roll and damping in yaw resulted in a very stable towed model.

INTRODUCTION

The National Aeronautics and Space Administration has undertaken a program to study the problems of piloted lifting-body reentry vehicle configurations in gliding flight and landing at subsonic speeds. Part of this program, described in reference 1, consisted of flight tests of a vehicle of a modified half-cone configuration through a wing-loading range from 7 to 20 pounds per square foot. This unpowered vehicle was to be towed up to altitude and released in free-gliding flight. In order to assist in the flight test program, the present study was made in the Langley full-scale tunnel to provide information on the tow behavior of the vehicle. In addition to the tow tests of the model, force tests were made in a low-speed tunnel with a 12-foot octagonal test section at

the Langley Research Center over an angle-of-attack range from $0°$ to $30°$ to determine the static stability and control characteristics. The results of tests made to determine the stability and control characteristics of an earlier configuration of the modified half-cone reentry vehicle in free flight are presented in reference 2.

Motion-picture supplement L-841 has been prepared and is available on loan. A request card and a description of the film are included at the back of this document.

SYMBOLS

The lateral data are referred to the body-axis system and the longitudinal data are referred to the wind-axis system. (See fig. 1.) Because of ballasting limitations the design center of gravity is below the test center of gravity and therefore the lateral data are presented about both positions. The coefficients are based on a planform area of 13.2 square feet, a mean geometric chord of 4.93 feet, and a span of 3.05 feet.

b	wing span, ft
$\bar{c}$	mean geometric chord, ft
C_D	drag coefficient, F_D/qS
C_L	lift coefficient, F_L/qS
C_l	rolling-moment coefficient, M_X/qSb
C_m	pitching-moment coefficient, $M_Y/qS\bar{c}$
C_n	yawing-moment coefficient, M_Z/qSb
C_Y	side-force coefficient, F_Y/qS
C_{l_p}	damping in roll, $\dfrac{\partial C_l}{\partial\left(\dfrac{pb}{2V}\right)}$
C_{l_r}	rolling moment due to yawing, $\dfrac{\partial C_l}{\partial\left(\dfrac{rb}{2V}\right)}$
$C_{l_\beta} = \dfrac{\Delta C_l}{\Delta\beta}$, per degree	

C_{n_p} yawing moment due to rolling, $\dfrac{\partial C_n}{\partial\left(\dfrac{pb}{2V}\right)}$

C_{n_r} damping in yaw, $\dfrac{\partial C_n}{\partial\left(\dfrac{rb}{2V}\right)}$

$C_{n_\beta} = \dfrac{\Delta C_n}{\Delta\beta}$, per degree

$C_{Y_\beta} = \dfrac{\Delta C_Y}{\Delta\beta}$, per degree

F_D drag, lb

F_L lift, lb

F_Y side force, lb

L/D lift-drag ratio, $\dfrac{C_L}{C_D}$

I_X moment of inertia about longitudinal body axis, slug-ft^2

I_Y moment of inertia about lateral body axis, slug-ft^2

I_Z moment of inertia about normal body axis, slug-ft^2

M Mach number

M_X rolling moment, ft-lb

M_Y pitching moment, ft-lb

M_Z yawing moment, ft-lb

p rolling velocity, radians/sec

q dynamic pressure, $\rho V^2/2$, lb/sq ft

r yawing velocity, radians/sec

R radius, in.

S wing area, sq ft

V free-stream velocity, ft/sec

W	weight, lb
W/S	wing loading, lb/sq ft
X,Y,Z	body reference axes unless otherwise noted
α	angle of attack, deg
β	angle of sideslip, deg
δ_e	elevon deflection (positive for trailing edge down measured from reference plane), deg
δ_f	deflection of either trailing-edge flap, positive for trailing edge down (neutral position defined as that position where flap is tangent to sloped upper surface of body), deg
$\delta_{f,a}$	differential deflection of trailing-edge trimmer flaps when used as ailerons for roll control, $\delta_{f,R} - \delta_{f,L}$ (neutral position defined as that position where flap is tangent to sloped upper surface of body), deg
$\delta_{f,e}$	deflection of trailing-edge flaps when used together as elevator for pitch control, $\dfrac{\delta_{f,R} + \delta_{f,L}}{2}$ (neutral position defined as that position where flap is tangent to sloped upper surface of body), deg
δ_r	rudder deflection for yaw control $\left(\text{positive when trailing edge is deflected to left, } \delta_{r,R} + \delta_{r,L}\right)$, deg
ϵ	inclination of principal axis of inertia, deg
ρ	air density, slugs/cu ft

Subscripts:

L	left
R	right

APPARATUS AND TESTS

Model

In order that the tunnel tow tests might be made in time to be of use in the full-scale flight program, the 1/3-scale model used in the previous wind-tunnel free-flight investigation (ref. 2) was used although the configuration was not exactly the same as that of the full-size vehicle. Alterations to the

model to make it conform more closely to the full-size vehicle included modification of the elevons, rudders, and trailing-edge flaps and the addition of a center fin and a canopy. (See fig. 2.) With these changes the only geometric difference between the model tested and the full-size vehicle was the cross-sectional shape of the afterbody. Whereas the model tested had cross sections which were essentially semicircular for the length of the body, the full-size vehicle cross section changed from semicircular to almost rectangular in the last 40 percent of the body length.

For the tow tests, the model controls were operated remotely by pilots by means of flicker (full on or full off) pneumatic servomechanisms which were activated by electric solenoids. Artificial stabilization in roll and in yaw was provided for some tests by simple rate dampers. An air-driven rate gyroscope was the sensing element, and the signal was fed into a servoactuator which deflected the trailing-edge flaps in proportion to the rolling velocity and the rudders in proportion to the yawing velocity. The roll damper added an increment in damping in roll $\left(\Delta C_{l_p}\right)$ of -1.0; but because of adverse yawing moments produced by the ailerons, the roll damper also added an increment in yawing moment due to rolling $\left(\Delta C_{n_p}\right)$ of about 0.5. The yaw damper produced two amounts of incremental damping in yaw $\left(\Delta C_{n_r}\right)$ of -2.0 and -4.0; but because of adverse rolling moments produced by the rudders, the yaw damper also added increments in rolling moment due to yawing $\left(\Delta C_{l_r}\right)$ of 0.8 and 1.6. Manual control was superimposed on the control deflection resulting from the rate signal. The trailing-edge flaps were operated together for elevator control and differentially for aileron control. The elevon surfaces were usually fixed but could also be linked to operate with the trailing-edge flaps.

A comparison of the mass characteristics of the model and of the full-size vehicle are presented in table I. The model was obviously too heavy to represent the lightest-weight vehicle (W/S = 7 lb/sq ft) used in low-speed flight studies, but better represents the vehicle at the higher wing loadings.

Test Equipment and Setup

The force tests were conducted at the Langley Research Center in a low-speed tunnel having a 12-foot octagonal test section. The model was sting mounted, and forces and moments were measured about the body axes with strain-gage balances.

Flight tests to study the dynamic stability and control characteristics of the model in towed flight were conducted in the Langley full-scale tunnel with the test setup illustrated in figure 3. An aircraft cable towline (1/16-inch-diameter, model scale, or 1/5-inch-diameter, full scale) was attached to the turning vanes ahead of the tunnel contraction. This arrangement resulted in a towline length of 140 feet, model scale, or 450 feet, full scale. An overhead cable, similar to the cable used in free-flight tests described in reference 3, supplied electric power and compressed air for the controls when the model was flown in the open-throat test section of the tunnel. Combined with

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this cable was a safety cable to prevent crashes should the motions become too violent and the model go out of control. The safety cable operator payed the cable in and out to keep it slack during the tests.

TESTS

Force Tests

In order to aid in the interpretation of the flight tests, force tests were made to determine the static longitudinal and lateral stability and control characteristics of the model. The tests were made at a dynamic pressure of 5.76 pounds per square foot, which corresponds to an airspeed of 69.5 feet per second at standard sea-level conditions and to a test Reynolds number of 2.2×10^6 based on the mean geometric chord of 4.93 feet.

Flight Tests

Flight tests were made to determine the dynamic stability and control characteristics of the model in towed flight. The tests were made at angles of attack from 14° to 18° for a towline-angle range from -5° (high tow) to 6° (low tow) and at tunnel speeds from 81 to 96 feet per second corresponding to a Reynolds number range from 2.5×10^6 to 3.0×10^6.

Flights were made with coordinated aileron and rudder control, with rudder-alone control, and with aileron-alone control. The control deflections used for most of the flights were $\delta_{f,a} = \pm 20^\circ$, $\delta_{f,e} = \pm 8^\circ$, and $\delta_r = \pm 17^\circ$ with the dampers not operating. When the roll damper was operating, the manual aileron control was reduced to $\pm 14^\circ$; and when the yaw damper was operating, the manual rudder control was reduced to $\pm 14^\circ$ for the lower amount of artificial damping in yaw and to $\pm 6^\circ$ for the higher amount.

STABILITY PARAMETERS OF THE MODEL

Static Longitudinal Stability and Control

The results of the static longitudinal stability and control tests are shown in figure 4 for an angle-of-attack range from 0° to 30° for trailing-edge flap deflections of 0°, -5°, -10°, and -20°. The flaps are shown in the 0° position in figure 2. The data of figure 4 show that the model has static longitudinal stability over the angle-of-attack range from 0° to 20° but that the stability decreases and the model becomes unstable as the angle of attack increases further. Upward deflection of the trailing-edge flaps produces nearly constant increments of pitching moment and appears to have very little effect on the static longitudinal stability. The data of figure 4 are referred to the test center of gravity but if referred to the design center of gravity the moment data would be virtually the same. The basic static longitudinal

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data appear to be in reasonably good agreement with corresponding data from reference 4 for a similar model tested at somewhat higher speed (M = 0.40) and Reynolds number $\left(4.45 \times 10^6\right)$. The differences which exist can probably be attributed to differences in canopy size and afterbody shape of the models.

Static Lateral Stability and Control

The static lateral stability characteristics of the model were determined over an angle-of-attack range from 0° to 30° for a sideslip range from -20° to $+20^\circ$. The results are presented in figure 5(a) for the complete model and in figure 5(b) for the model without the center fin. These data are summarized in figures 6 and 7 in the form of the stability derivatives C_{Y_β}, C_{n_β}, and C_{l_β} plotted against angle of attack. The values of these derivatives were obtained from the differences between the values of the coefficients measured at sideslip angles of 5° and -5°. Since the data of figure 5 show some non-linearity at the larger sideslip angles, the derivatives presented in figures 6 and 7 are only used to indicate trends and to provide comparisons of the configurations for the sideslip range from 5° to -5°.

The data of figures 6 and 7 show that both the complete model and the model without the center fin have positive directional stability and effective dihedral over the angle-of-attack range, although the directional stability of the model without the center fin is very low for a small angle-of-attack range near 20°. The comparisons made in figure 7 indicate that, as expected, the directional stability $\left(C_{n_\beta}\right)$ is higher for the complete model than for the model with the center fin off; however, the center fin had virtually no effect on the effective-dihedral parameter $\left(-C_{l_\beta}\right)$. These results generally agree with the data presented in reference 4. Figure 6 shows that the effective dihedral is greater when referred to the design center of gravity than when referred to the test center of gravity directly above it and that the increment is generally constant.

The rudder effectiveness of the model is shown in figure 8. The yawing moments produced by the rudders decreased by more than 50 percent as the angle of attack increased. Adverse rolling moments due to yawing moments were appreciable, with values of approximately 40 percent of the yawing moments.

The aileron effectiveness of the trailing-edge flaps deflected differentially from elevator trim settings $\left(\delta_{f,e}\right)$ of 0° and -10° is shown in figure 9. The rolling effectiveness of the flaps was only about one-half as great for deflection from the 0° trim setting as from the -10° trim setting. This result would seem to indicate the presence of separated flow, or a very thick boundary layer, over the flaps for the 0° trim setting; and such a condition would not be surprising in view of the large upper-surface boattail angle of the body. The data of figure 9 also show that the rolling moments were accompanied by adverse yawing moments approximately one-half as large as the rolling moments.

FLIGHT-TEST RESULTS AND DISCUSSION

A motion-picture film supplement (film serial L-841) covering flight tests of the model has been prepared and is available on loan.

Most of the tow tests were made at towline angles between -5° (high tow) and 6° (low tow) and at airspeeds of about 92 feet per second (model scale) to simulate the towline angles and velocity conditions for ground tow and initial air tow. The lift coefficient for the model tests was considerably higher, however, than that expected for the flight vehicle on tow because of the much higher-than-scale wing loading of the model.

Longitudinal Stability

The longitudinal stability was generally satisfactory. Occasionally, a disturbance would excite a short-period (about 1 second) forward and backward translational motion of small amplitude (about 7 percent of body length). This longitudinal motion was stable and was damped out in several cycles. The oscillation was caused by resilience of the tow cable which had a spring constant of about 1.5 pounds per inch. This resilience of the cable resulted more from the straightening of the catenary than stretch of the cable.

Lateral Stability and Control

Basic configuration.- The tow tests showed that the model in the basic configuration had two undesirable stick-fixed stability characteristics - (1) a lightly damped Dutch roll oscillation, and (2) an unstable long-period oscillation of a type which is sometimes called a towline oscillation.

The lightly damped Dutch roll oscillation had a period of about 1 second. It was generally pilot-excited through control inputs and required at least three cycles to damp completely. This motion could be controlled by careful use of coordinated rudder and aileron control.

The unstable long-period oscillation consisted of sidewise displacement and rolling motions which were large relative to the yawing motions. The characteristics of the long-period oscillation appeared to be unaffected by towline angle for the range of this investigation (-5° high tow to 6° low tow). If the lateral motions were not controlled, the model would diverge out of the test section of the tunnel in less than one cycle; but, because of the relatively long period of the oscillation (about 6 seconds, model scale, or 11 seconds, full scale), the motions could be easily controlled by careful use of coordinated rudder and aileron control or rudder-alone control. However, sustained flights with aileron-alone control were impossible, probably because of the relatively large unfavorable yawing moments accompanying the rolling moments. (See fig. 9.) The model was not flown with the outboard elevons used alone for roll control, but subsequent investigations have shown that elevons alone can provide acceptable roll control for the flight vehicle. The elevons were not

used alone in the present study because the control data of reference 2 had indicated that the yawing moments accompanying the rolling moments produced by the trailing-edge flaps were smaller than those produced by the outboard elevons in the angle-of-attack range which was somewhat higher for the model (14° to 18°) than for the test vehicle (3° to 12°).

The overall lateral stability and control characteristics of the basic model in towed flight were considered unsatisfactory for general operation but acceptable for the type of operation envisioned for the research glider - that is, for relatively short periods of towed flight under visual flight conditions.

Model without center fin.- A few tests were made with the center fin removed; and although the model was found to be slightly more difficult to control in this configuration than in the basic configuration, the difference was not significant.

Addition of damping in roll.- The addition of roll rate damping $\left(\Delta C_{l_p} = -1.0 \text{ and } \Delta C_{n_p} = 0.5\right)$ to improve the lateral stability characteristics of the model greatly increased the damping of the Dutch roll oscillation so that this motion was no longer apparent; however, the added damping had virtually no effect on the unstable translational oscillation. Although constant use of control was required to prevent the divergence of this long-period oscillation, the control task was easier with the additional roll damping and the flights were somewhat smoother.

Addition of damping in yaw.- Two amounts of yaw rate damping were added to improve the lateral stability characteristics. The smaller amount of artificial damping in yaw $\left(\Delta C_{n_r} = -2.0 \text{ and } \Delta C_{l_r} = 0.8\right)$ improved the stability so that the model could be controlled with ailerons alone, although rudder-alone control and coordinated aileron and rudder control were more satisfactory. With the larger amount of damping in yaw $\left(\Delta C_{n_r} = -4.0 \text{ and } \Delta C_{l_r} = 1.6\right)$ the tow characteristics of the model were even more satisfactory. The translational oscillation and Dutch roll oscillation were both stable, but the Dutch roll was not as well damped as it was with the roll damper operating.

Addition of damping in roll and yaw.- The most stable tow condition was obtained when both artificial roll and yaw damping $\left(\Delta C_{l_p} = -1.0 \text{ and }\right.$ $\left. \Delta C_{n_r} = -2.0\right)$ were added. The damping of both the translational and the Dutch roll oscillations were deadbeat in the two best configurations - (1) the configuration with center fin on, level tow, and elevons trimmed at -20°, and (2) a similar configuration with the elevons trimmed at -30° but linked to move with the trailing-edge control surfaces. When the elevons were fixed at trim angles of 0° or -30°, however, the translational oscillation was only lightly damped even though the towline angle and angle of attack were the same as for the configuration with the elevons fixed at -20°. No explanation for this result is apparent. The tow condition for artificial roll damping in conjunction with the larger amount of yaw damping $\left(\Delta C_{n_r} = -4.0\right)$ was not investigated.

CONCLUSIONS

The results of an investigation in the Langley full-scale tunnel to study the stability and control characteristics of a towed model of a lifting-body reentry model can be summarized as follows:

1. The longitudinal stability was generally satisfactory.

2. The lateral stability of the basic configuration was unsatisfactory because of a combination of a lightly damped Dutch roll oscillation and an unstable long-period oscillation which consisted of large amounts of roll and sidewise motion compared with the yaw displacements.

3. The basic model could be controlled fairly easily by use of coordinated rudder and aileron control and by rudder-alone control, but it was uncontrollable with aileron-alone control.

4. The foregoing combination of stability and controllability was considered unsatisfactory for general operation but acceptable for relatively short periods of operation under visual flight conditions.

5. The addition of artificial damping in roll made the flights smoother and the control easier, but the model was still unstable. The addition of artificial damping in yaw made the model stable, but the rolling oscillation was damped only moderately well. Addition of both damping in roll and damping in yaw resulted in a very stable towed model.

Langley Research Center,
    National Aeronautics and Space Administration,
        Langley Station, Hampton, Va., October 27, 1964.

REFERENCES

1. Thompson, Milton O.: Results of the Lifting-Body Flight Program. Proceedings of the 1963 "Report to the Aerospace Profession," Soc. Exptl. Test Pilots, Sept. 1963, pp. 147-164.

2. Hassell, James L., Jr.; and Ware, George M.: Investigation of the Low-Subsonic Stability and Control Characteristics of a 0.34-Scale Free-Flying Model of a Modified Half-Cone Reentry Vehicle. NASA TM X-665, 1962.

3. Paulson, John W.; and Shanks, Robert E.: Investigation of Low-Subsonic Flight Characteristics of a Model of a Hypersonic Boost-Glide Configuration Having a 78° Delta Wing. NASA TN D-894, 1961. (Supersedes NASA TM X-201.)

4. Spencer, Bernard, Jr.; and Phillips, W. Pelham: Low-Speed Aerodynamic Charteristics of a Modified Blunt 13° Half-Cone Lifting-Body Configuration Having Deployable Horizontal Tails With or Without Variable-Sweep Wings. NASA TM X-847, 1963.

TABLE I.- MASS CHARACTERISTICS OF MODEL AND FULL-SIZE VEHICLE

Characteristics	Model	Model, scaled up	Full-size vehicle
W, lb	68	2,310	970 to 2000
I_X, slug-ft^2 . . .	1.63	583	200 to ----
I_Y, slug-ft^2 . . .	8.39	3,000	868 to ----
I_Z, slug-ft^2 . . .	9.13	3,270	920 to ----
W/S, lb/sq ft . . .	5.15	16.6	7 to 20
ϵ, deg	0	0	------------
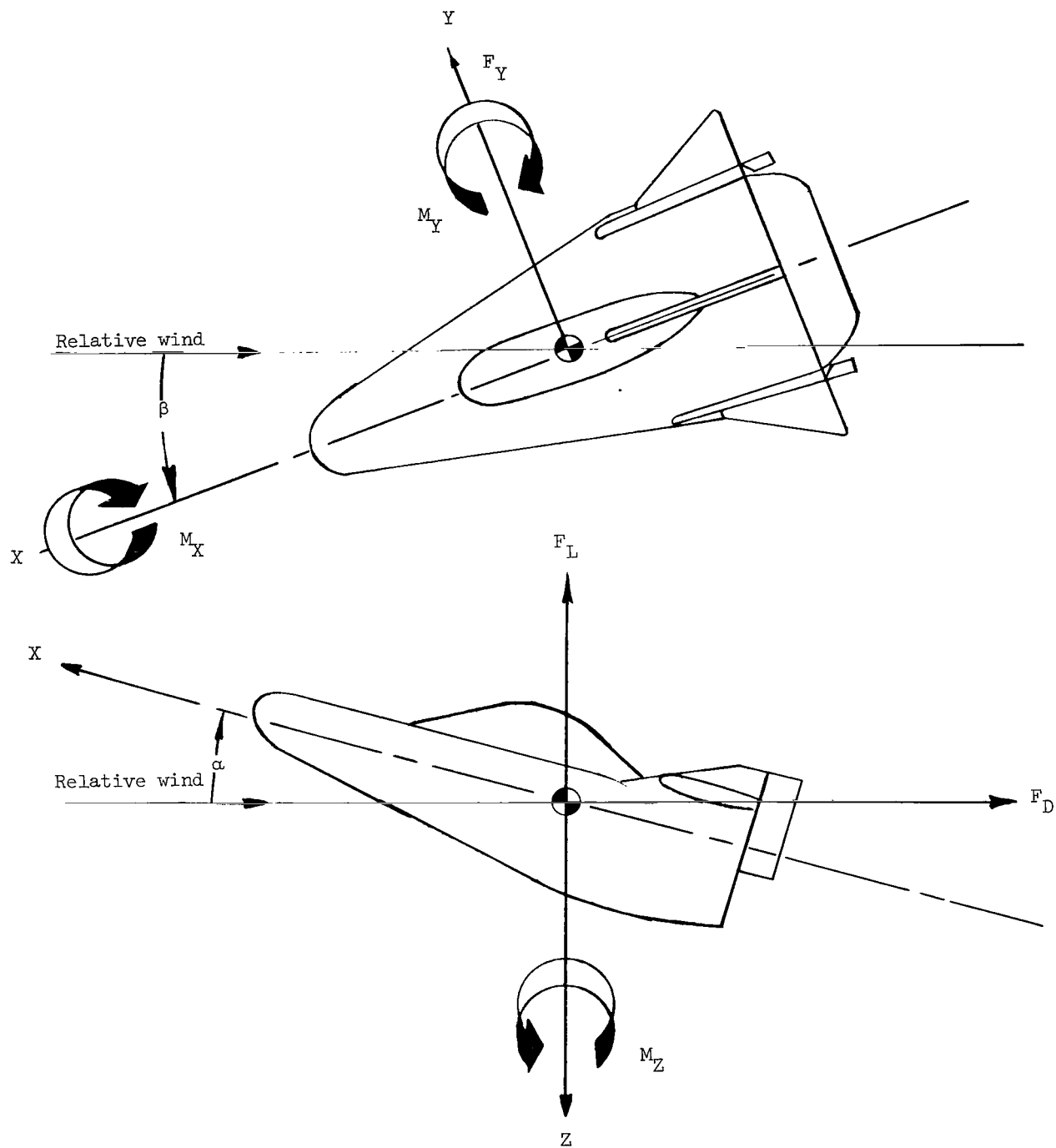
Figure 1.- Sketch of axis systems used in investigation. Arrows indicate positive directions of forces, moments, and angles.
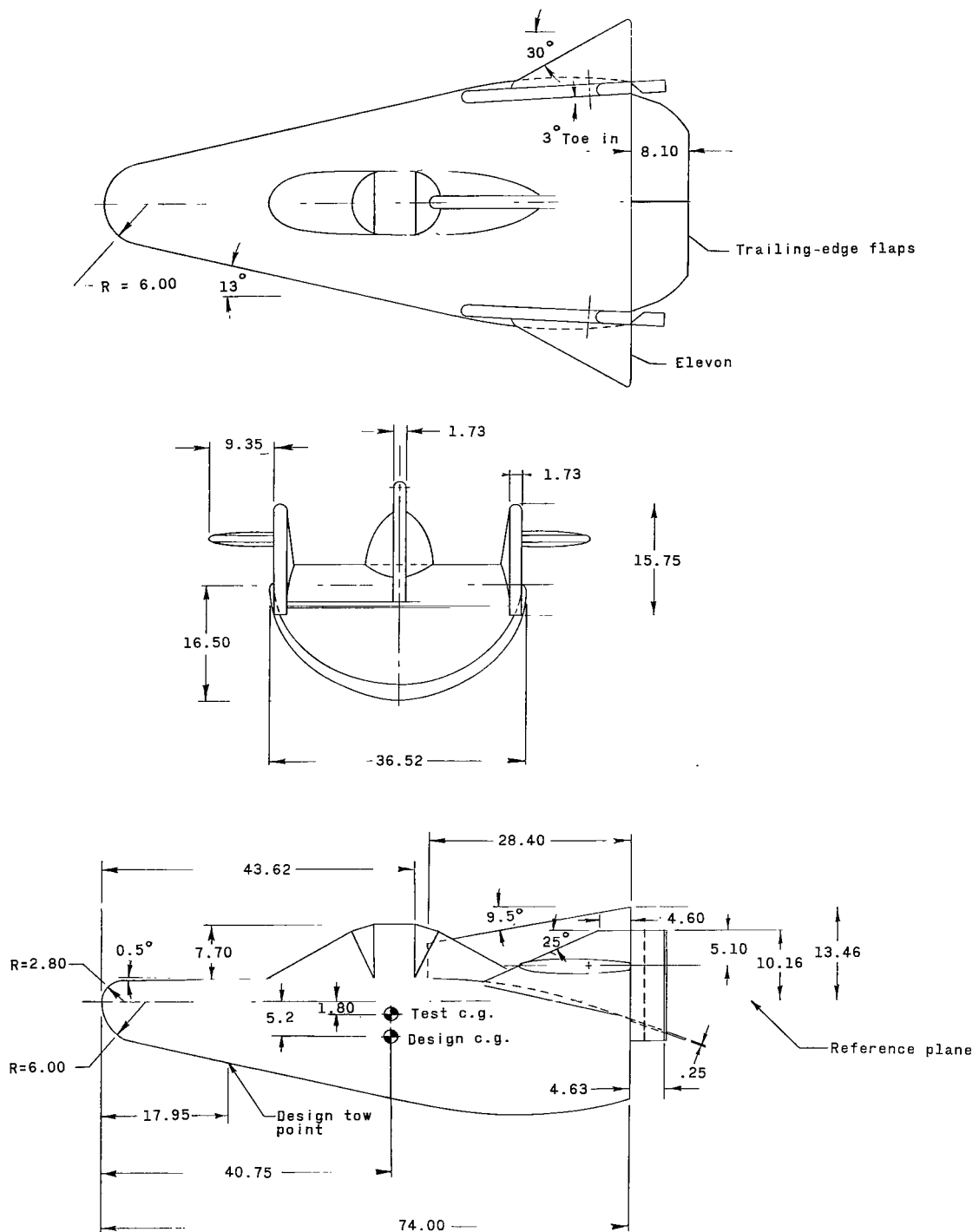
Figure 2.- Three-view drawing of a model used in investigation. Rudder and trailing-edge flap dimensions given in chord plane. All dimensions are in inches.

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Overhead cable

Forward towline attachment
at tunnel turning vanes

140-foot towline

Wind direction
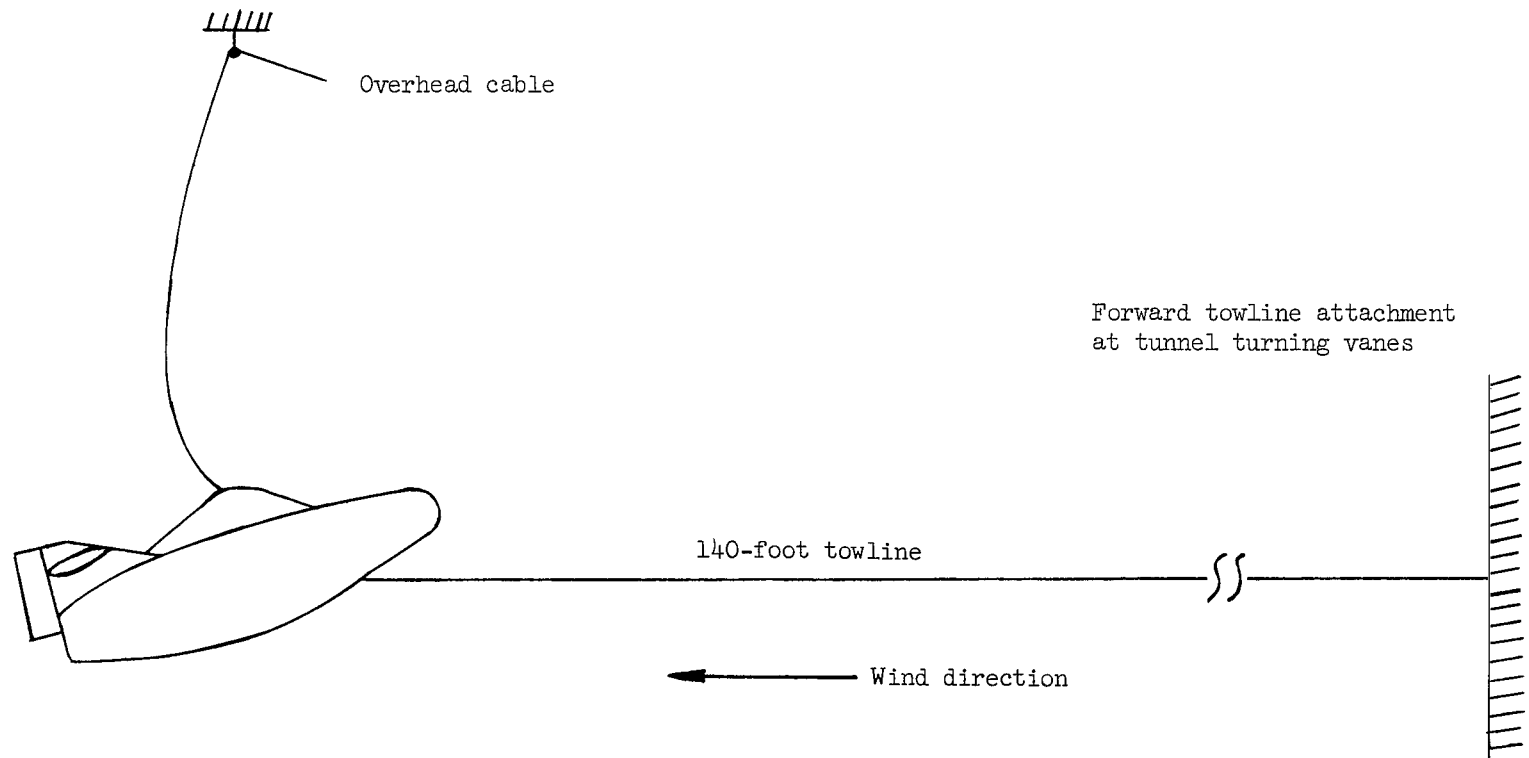
Figure 3.- Test setup used for towing the model.
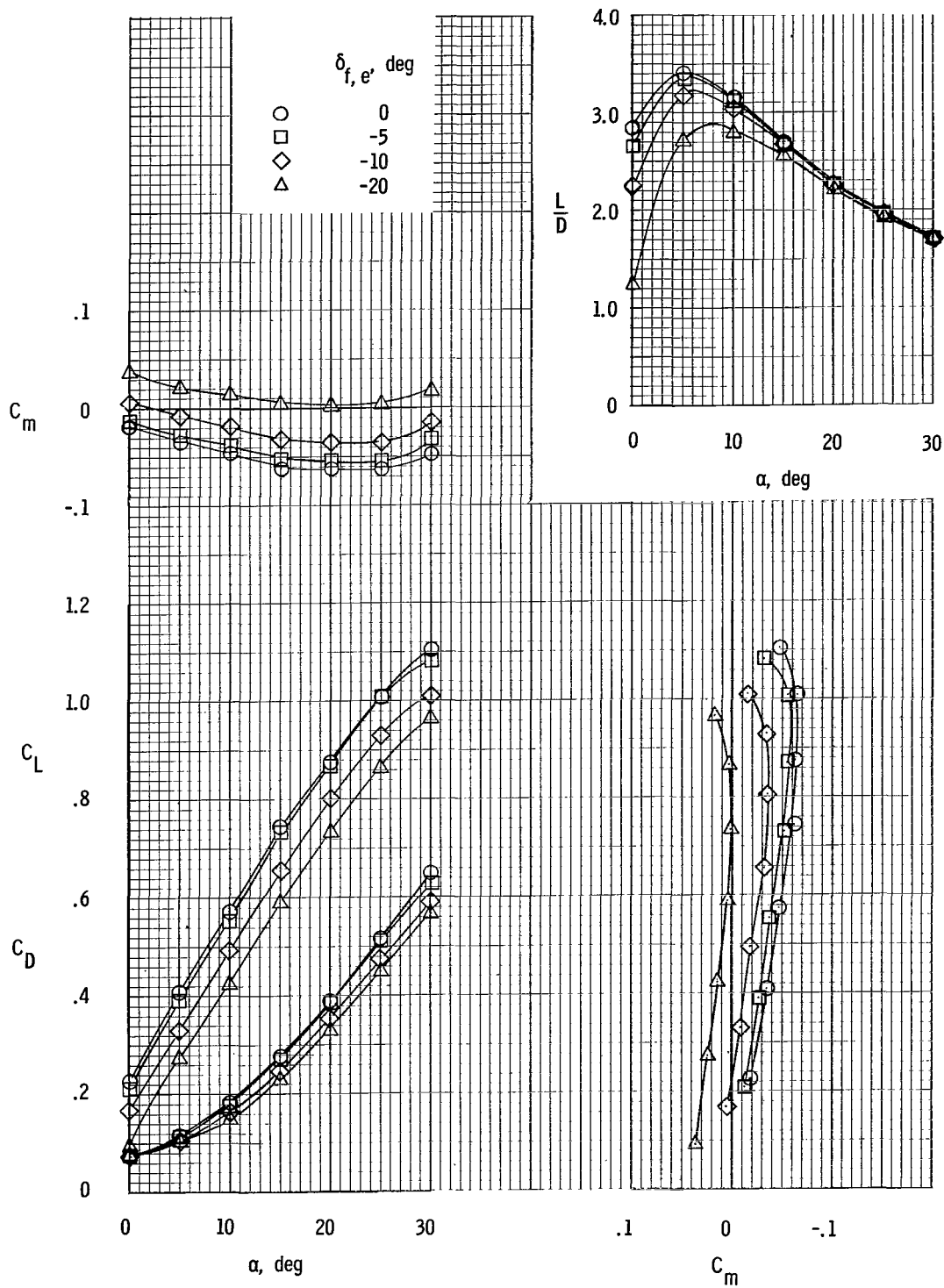
Figure 4.- Effect of trailing-edge flap deflection on the longitudinal characteristics of the model. $\delta_e = 0°$; $\beta = 0°$.

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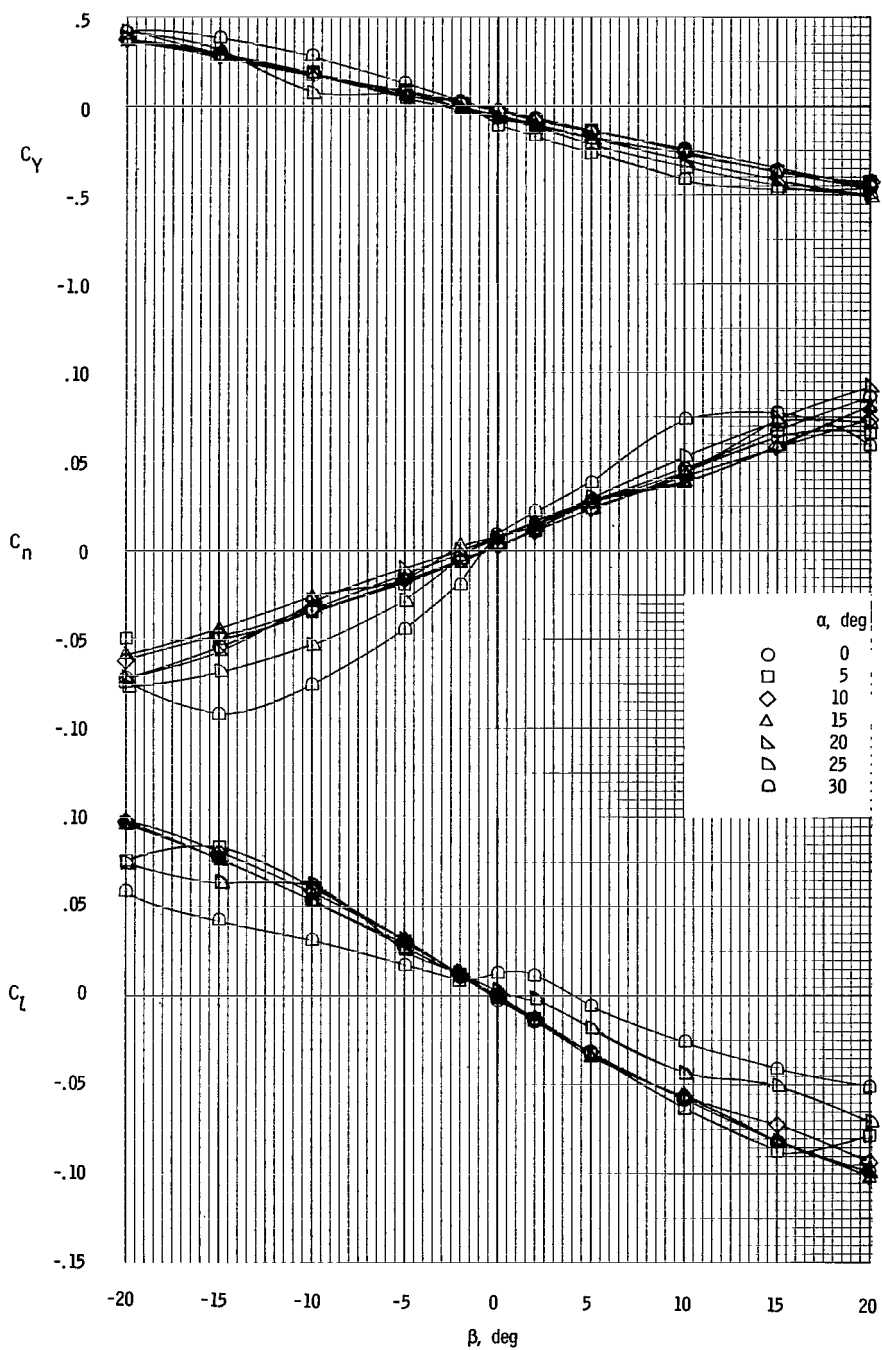
(a) Complete model.

Figure 5.- Variation of static lateral coefficients with angle of sideslip. $\delta_{f,e} = 0^{\circ}$; $\delta_e = 0^{\circ}$; test center of gravity.

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C_Y

C_n

C_l

.5

0

-.5

.10

.05

0

-.05

-.10

.10

.05

0

-.05

-.10

-20   -15   -10   -5   0   5   10   15   20

β, deg

	α, deg
◯	0
□	5
◇	10
△	15
◁	20
◺	25
⬠	30
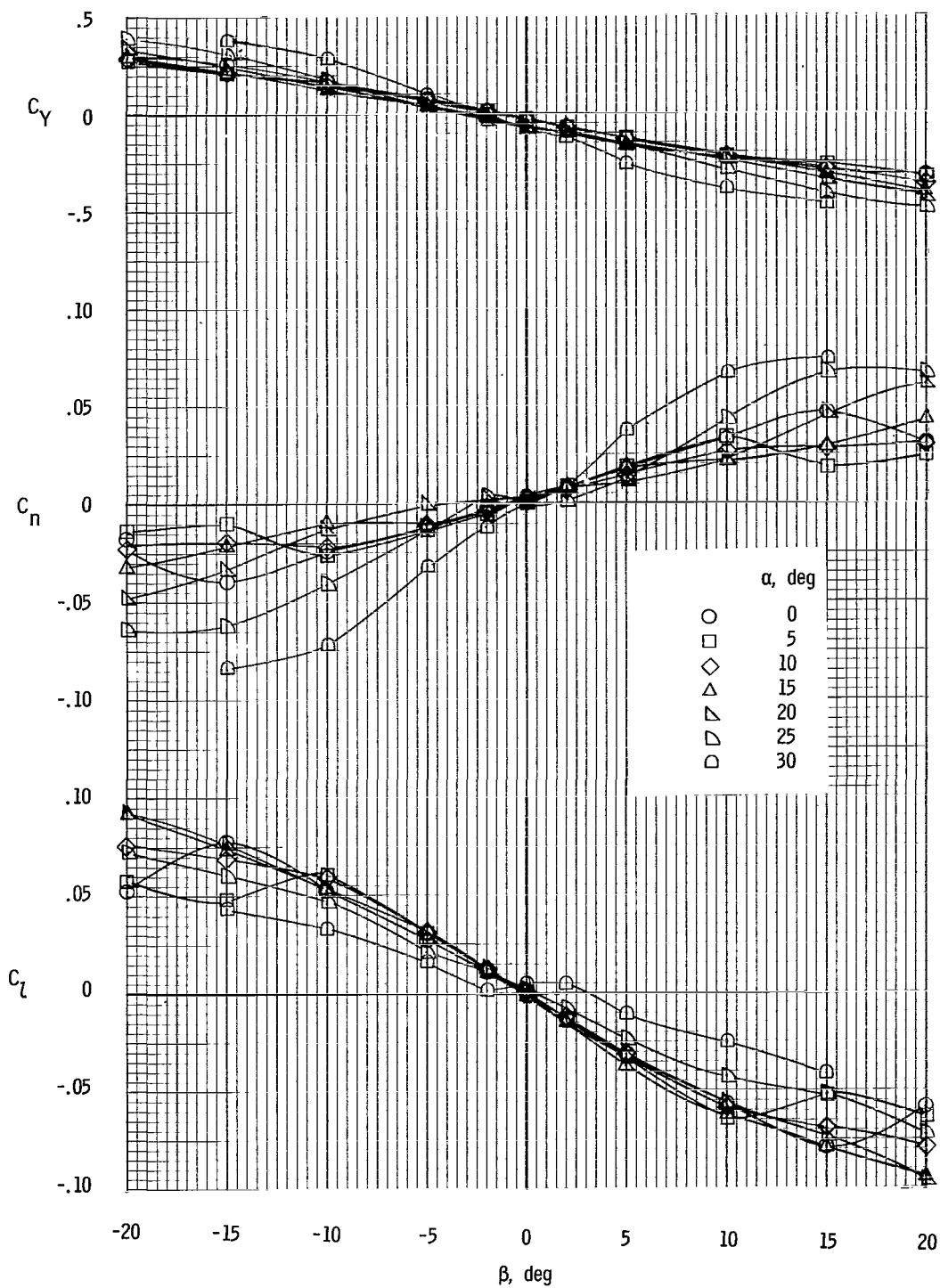
(b) Center fin off.

Figure 5.- Concluded.
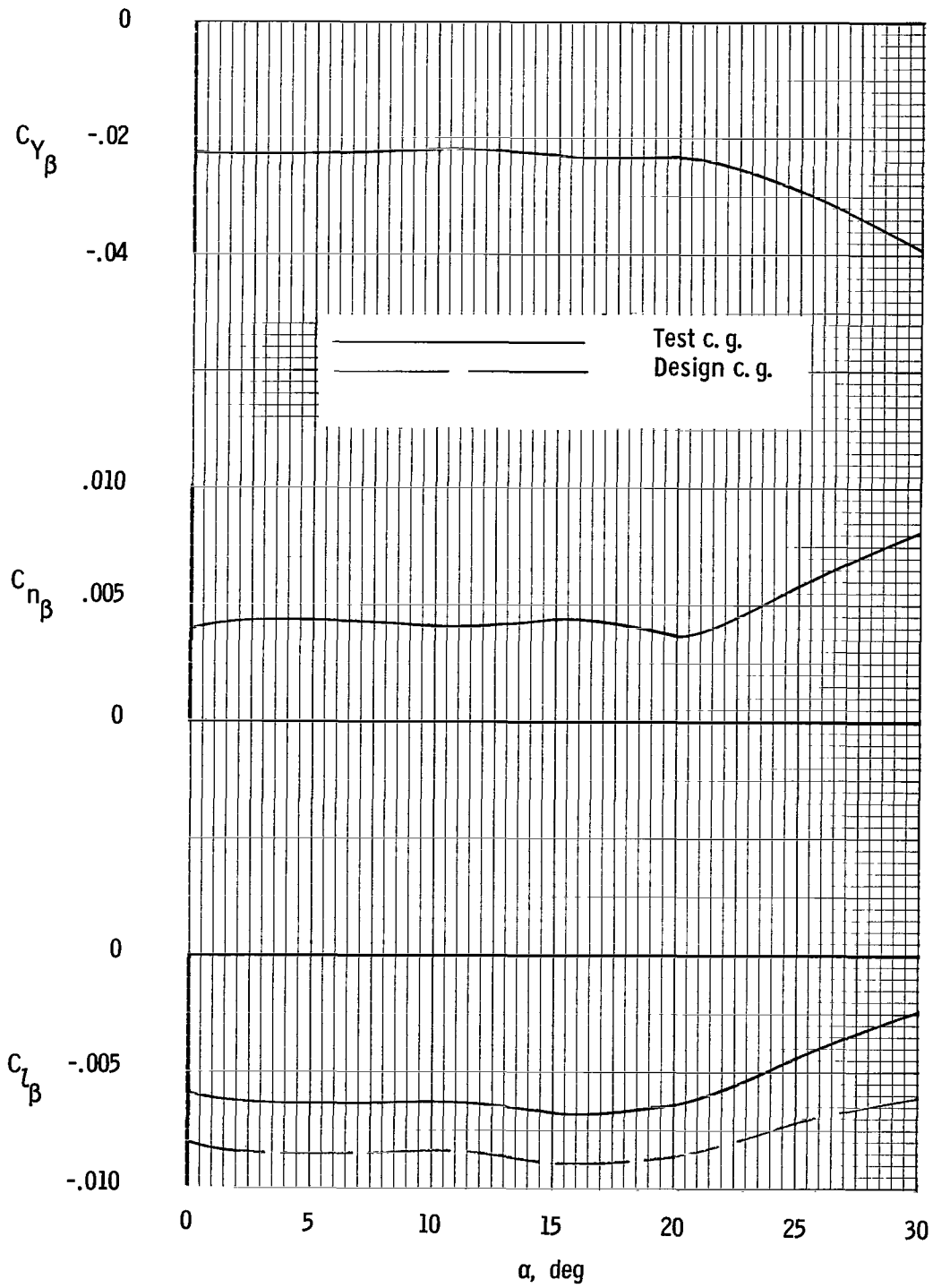
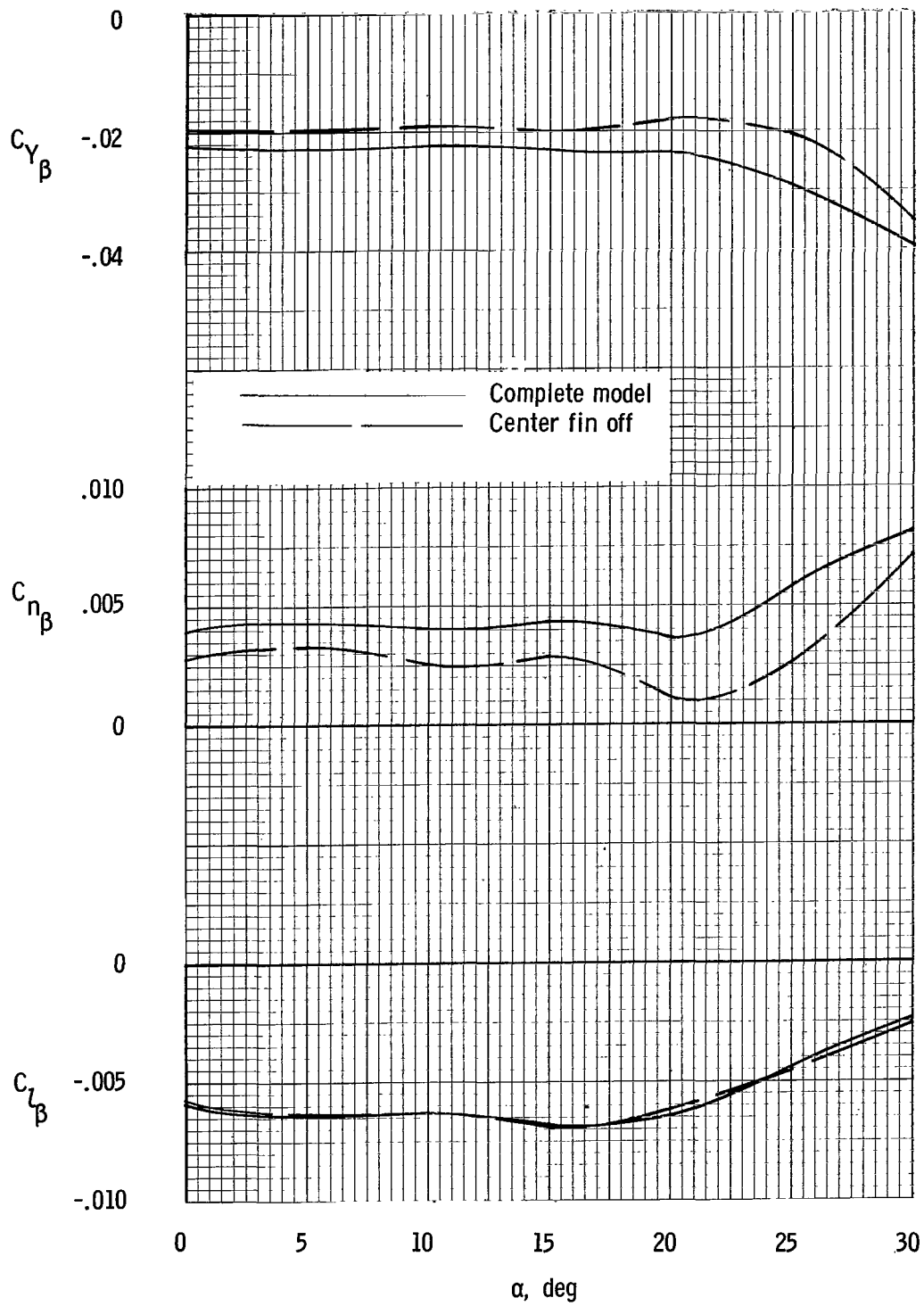Figure 6.- Variation of static lateral derivatives with angle of attack. $\delta_{f,e} = 0^{\circ}$; $\delta_e = 0^{\circ}$.

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Figure 7.- Effect of center fin on the static lateral stability derivatives of the test model. $\delta_{f,e} = 0^o$; $\delta_e = 0^o$.
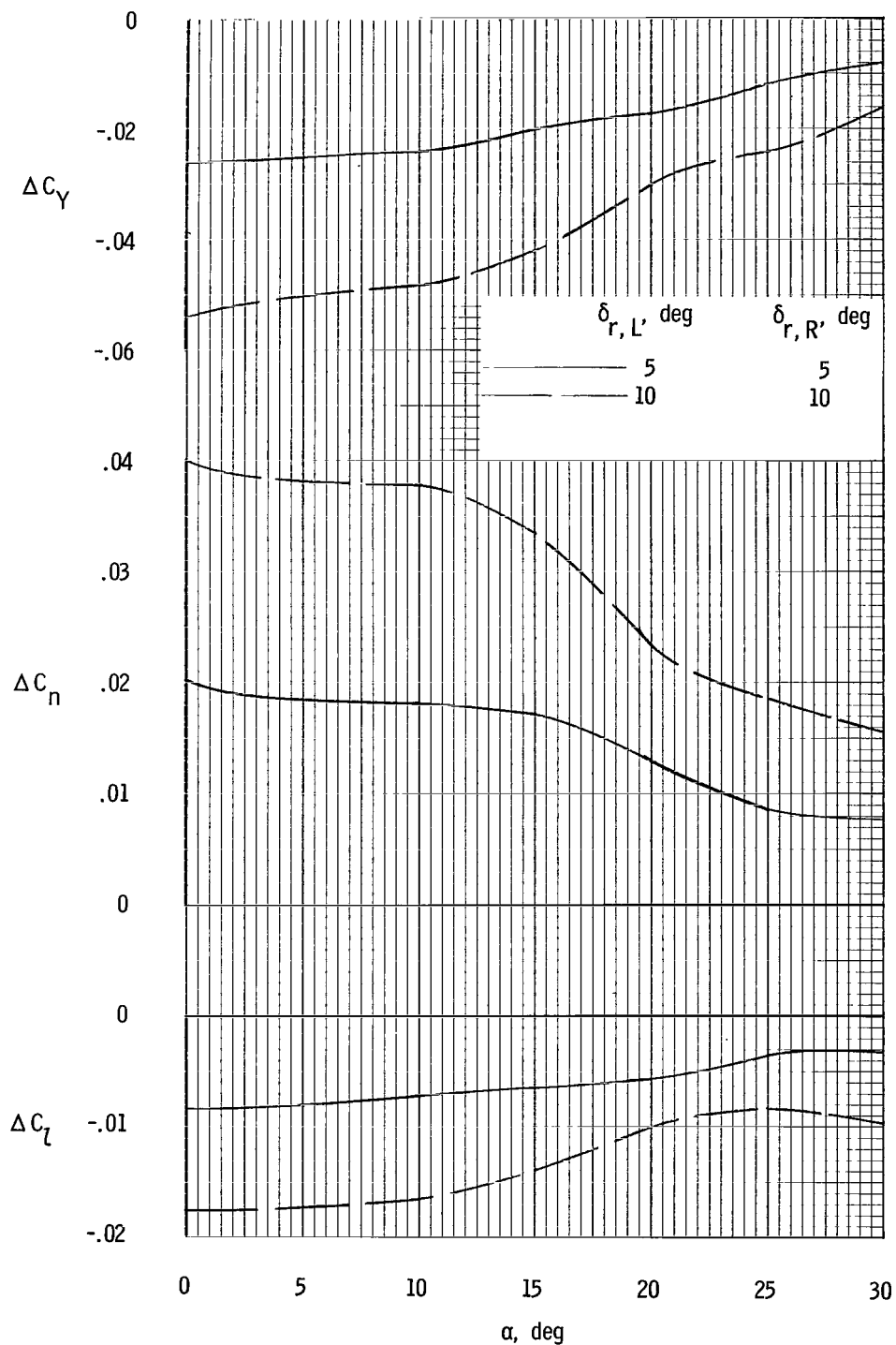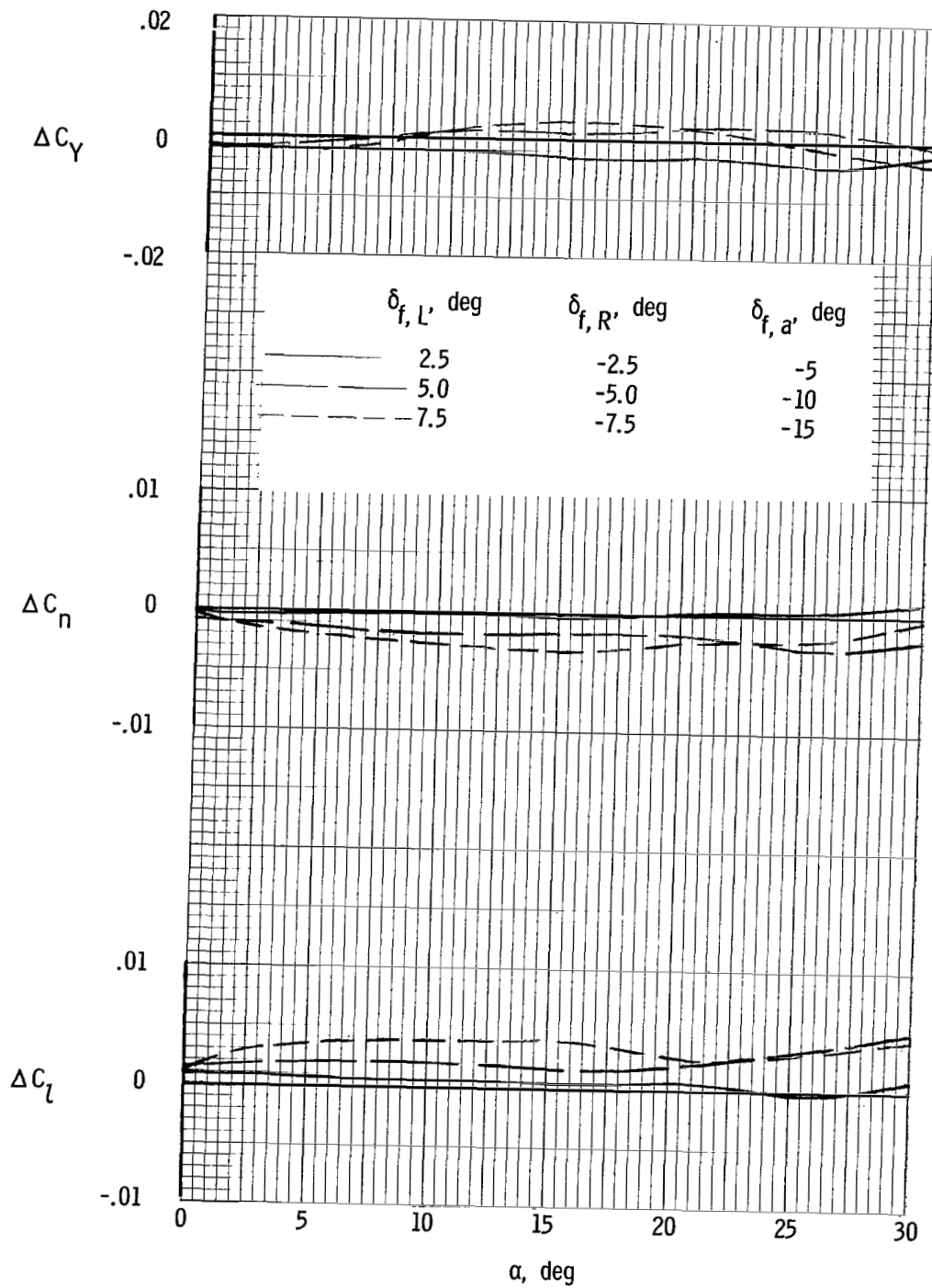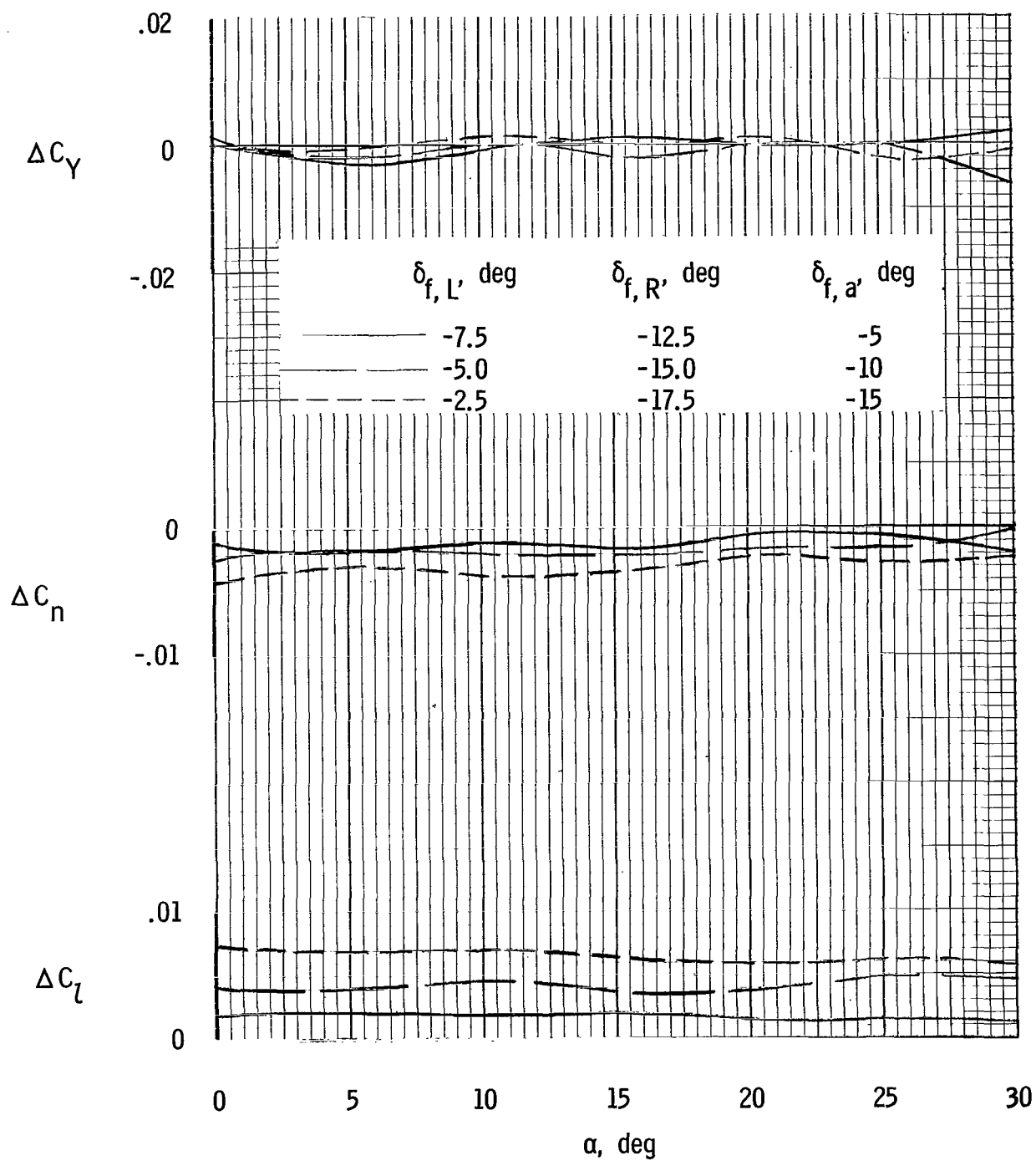
Figure 8.- Incremental lateral control coefficients due to rudder deflection. $\delta_{f,e} = 0^{o}$; $\delta_e = 0^{o}$; $\beta = 0^{o}$.

(a) $\delta_{f,e} = 0^o$.

Figure 9.- Incremental lateral control coefficients due to aileron deflection.
$\delta_r = 0^o$; $\delta_e = 0^o$; $\beta = 0^o$.

$\delta_{f,L}$, deg	$\delta_{f,R}$, deg	$\delta_{f,a}$, deg
-7.5	-12.5	-5
-5.0	-15.0	-10
-2.5	-17.5	-15

(b) $\delta_{f,e} = -10^{\circ}$.

Figure 9.- Concluded.

A motion-picture film supplement L-841 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 10 min, color, silent) illustrates the low-speed stability and control characteristics of a towed modified half-cone reentry vehicle. The effects of artificial damping in roll and of artificial damping in yaw on the stability characteristics are shown.

Requests for the film should be addressed to:

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NASA Langley Research Center
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City and State   Zip code

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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